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Al/Al₂O₃ Metal Matrix Composites (MMCs) and Macrocomposites for Armor Applications

**by Prashant Karandikar, Eric M. Klier, Matthew Watkins,
Brandon McWilliams, and Michael Aghajanian**

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**A reprint from *Proceedings of the 37th International Conference and Exposition on Advanced Ceramics and Composites (ICACC)*,
Daytona Beach, FL, 27 January–1 February 2013.**

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Al/Al₂O₃ MMCs AND MACROCOMPOSITES FOR ARMOR APPLICATIONS

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ABSTRACT

Metal matrix composites (MMCs) combine the desirable characteristics of metals (ductility and thermal conductivity) and ceramics (high hardness, high stiffness, low thermal expansion). In this study, Al/Al₂O₃ MMCs with alumina particle contents ranging from 12% to 46% were fabricated by different processing approaches. Microstructures and properties (density, elastic modulus, tensile strength, ductility – failure strain, and thermal expansion) of these MMCs were characterized. Al/Al₂O₃ MMCs showed higher ductility than Al/SiC MMCs. As the measured ductility was still less than that necessary for multi-hit armor applications, a macrocomposite concept was developed. This concept utilizes incorporation of high strength, higher-CTE (coefficient of thermal expansion) ductile macroscopic reinforcements in the MMC to induce residual compressive stress in the MMCs with an intent of enhancing ductility. Numerical modeling on an example macrocomposite system showed that residual compressive stresses can indeed be generated. Specimens were designed to test the numerical predictions and generate data for designing a macrocomposite system. A process was developed and applied successfully to fabricate the macrocomposite specimens.

INTRODUCTION

A variety of materials are used for the construction of armor for personnel, vehicles, and aircraft. Properties of some of the most commonly used armor materials are summarized in Table 1. Depending on the projectile to be defeated, one or more of these materials are needed in the form of a “system”. The components of the system have to work synergistically to achieve projectile defeat. For example, many of the current armor solutions require a combination of a ceramic to blunt the projectile and a ductile backing to catch the fragments^{1, 2}. For multi-hit requirements, ceramics are typically used as a mosaic of tiles or cylinders¹. Two examples of the use of an array or mosaic of ceramics are (a) ceramic cylinders in a polymeric matrix (e.g. LIBA, SURMAX, SMART armor)¹ with or without a metal backing, and (b) SiC tiles encapsulated in titanium (Ti) produced by hot pressing¹. One critical aspect of the encapsulation approach is the prevention of cracking in the ceramic due to the CTE mismatch-induced residual stresses. In the Ti-SiC system¹, residual compressive stresses are generated in the ceramic due to the higher CTE metal surrounding it. This residual stress increases dwell, and the confined ceramic debris provides the erosive phase of projectile defeat.

Table 1. Summary of properties of typical armor materials

Material	ρ (g/cc)	E (GPa)	σ (MPa)	K_{IC} (MPa-m ^{1/2})	Elongation (%)	Hardness	AD (psf) [†]	CTE ppm/K
UHMWPE Spectra 2000	0.97	124	3340*	N/A	3	N/A	5.0	100
5083 Al -H32	2.66	72	320*	43	17	54 RB	13.8	25
RHA	7.86	207	1110*	75	14	99 RB	40.9	13.2
Mild Steel 1018	7.8	210	634	40	27	120B	40.6	13.4
304 SS (annealed)	8.03	200	490	88	40	201B	41.6	16.6
Ti-6-4	4.43	114	940*	60	16	334B	23.0	10.6
Al_2O_3 CAP-3	3.90	370	379	4-5	0.10	1292	20.2	6.0
Hot Pressed B_4C Ceralloy-546 4E	2.50	460	410	2.5	0.09	2066	13.0	5.1
Hot Pressed SiC-N	3.22	453	486	4.0	0.10	1905	16.7	3.0
Sintered SiC Hexoloy	3.13	410	380	4.6	0.09	1924	16.2	3.0
SiC (RBSC)	3.03	380	260	4.0	0.07	1332	15.7	2.9
$\text{B}_4\text{C}/\text{Si}$ (RBBC)	2.56	390	271	5.0	0.07	1626	13.3	4.8
TiB_2 Ceralloy 225	4.50	540	265	5.5	0.05	1849	23.4	8.1

ρ – density; E – Young's modulus; σ – flexural/tensile* strength; K_{IC} – fracture toughness; Hardness for metals Rockwell B or Brinell, for ceramics - Knoop 2kg; AD – areal density, CTE – coefficient of thermal expansion (20-100°C)

Sources: Spectra: Honeywell; CAP-3: CoorsTek; Ceralloy, Ekasic-T: Ceradyne; Hexoloy: Saint Gobain; SiC-N: Cercom (CoorsTek); RBSC, RBBC: M Cubed Technologies (MCT). Properties for other manufacturer's materials are from their respective websites/datasheets except for 2kg Knoop hardness †Areal density (lb/sf -psf): weight of 12 x 12 x 1 inch panel in pounds

Aluminum and aluminum based MMCs could offer a lower-cost alternative (to HIPed Ti) for encapsulation of ceramic tiles for armor applications. MMCs combine the desirable characteristics of metals (ductility, thermal conductivity) and ceramics (high hardness, high stiffness, low thermal expansion). In addition, the CTE of MMCs can be tailored to match more closely to the CTE of the ceramic being encapsulated. This would lower the residual stresses and reduce the potential for cracking of the ceramic or encapsulating material and warping of the macro composite during processing.

Aluminum-SiC particulate MMCs (Al/SiC)⁴⁻⁵ have been used successfully in a variety of applications in large tonnage. Al/SiC MMCs also provide desirable properties for armor applications (high hardness, high stiffness, and light weight). However, for SiC-based MMCs, matrix Al has to be alloyed with Si (>8%) to prevent formation of the deleterious Al_4C_3 . Unfortunately, Si alloying reduces the ductility of the alloy and the MMC. For most armor applications, ductility of the encapsulant material is very critical for achieving multi-hit capability. If the SiC particulates are replaced with Al_2O_3 particulates, the requirement for Si in the matrix alloy is eliminated and more ductile matrix alloys can be selected. As a result, an MMC with higher ductility can be achieved.

Liu et al.^{6, 7} have reported on the effect of superimposed hydrostatic pressure on deformation and fracture of $\text{Al}/\text{Al}_2\text{O}_3$ MMC (15% particles). At 300 MPa of superimposed pressure, the reduction in area changed from 10% to 80% and the failure strain was quadrupled. Thus, very significant increase in ductility was achieved. The main mechanism for ductility increase was suppression of void generation and cracking of the alumina particles.

In this work, $\text{Al}/\text{Al}_2\text{O}_3$ MMCs with various alumina contents were made. Properties of these were characterized. To further enhance multi-hit capability of the MMC-based armor solution, a macrocomposite concept was developed. In this concept, a higher-CTE (higher CTE than the CTE of the

MMC), high-ductility material, such as austenitic stainless steel in the macroscopic form (wire, sheet, expanded sheet, perforated sheet, corrugated sheet, 3-D structure, etc.), is incorporated in the MMC to induce residual compressive stresses and further increase its ductility. Numerical modeling was conducted on an example system to assess if residual compressive stresses can be generated. Specimens were designed to test the numerical predictions and assess the effect on MMC ductility. Processes were developed and applied successfully to fabricate the macrocomposite test specimens.

EXPERIMENTAL PROCEDURE

MMC plates (150 mm x 200 mm x 6 mm) with varying alumina reinforcement content from 12 to 46% were produced by a casting technique. Two different types of matrix alloys were used: Al-4Mg and Al-1Mg-0.6Si-0.4Cu. For comparative evaluation, plates were also cast out of 170.1 aluminum alloy and 170.1 + 4Mg alloy. Wetting between ceramic particles and the matrix was achieved by either mechanical means or chemical means (PRIMEX³). Small samples were cut from these MMCs, potted, and polished for microstructural observations. Tensile test samples and CTE measurement samples were machined from the composite plates. Tensile testing was conducted on flat dog-bone shaped specimens (ASTM B557). For each plate 5 tensile specimens were tested and average values were reported. CTE testing was conducted on 5 x 5 x 25 mm sample using a Netzsch TMA 402 F1 at a heating rate of 5°C/minute from -20°C to 500°C with a helium purge gas. The system influence (sample holder expansion) was corrected by a calibration measurement of a fused silica standard. The calibration run was carried out under the same conditions as used for the test samples. Measurements were made on two samples for each material and an average value was reported. In all cases both samples showed similar/reproducible results.

PROPERTIES OF Al/Al₂O₃ MMCs

Microstructures of Al/Al₂O₃ MMCs with various reinforcement contents are shown in Figure 1. The microstructures clearly show the different alumina particle contents in the different MMCs. The matrix alloy, alumina volume fraction, densities, mechanical properties, and thermal properties are summarized in Table 2. Mechanical and thermal properties are plotted in Figures 2-6. Mechanical property data for the Al/SiC MMCs (Al-10Si matrix) are also included for comparison^{4, 5}. The data in Figures 2 through 6 shows that elastic modulus and strength increase with Al₂O₃ volume fraction. Failure strain (elongation), on the other hand, decreases as the Al₂O₃ volume fraction is increased. Failure strain is also dependent on the matrix alloy selection. As is well known^{4,5}, elastic modulus does not follow the rule of mixtures (linear increase with particle volume fraction) for particulate MMCs. The coefficient of thermal expansion (CTE) decreases as the alumina particle content is increased.

Al/Al₂O₃ MMCs with Al-1Mg-0.6Si-0.4Cu matrix showed the highest failure strain, followed by Al/Al₂O₃ MMCs with Al-4Mg matrix, and the Al/SiC MMCs with Al-10Si alloy matrix showed the lowest failure strain. The failure strain of Al/Al₂O₃ was still lower than that desired for armor applications, especially as encapsulants for ceramic tiles. Therefore, other means of increasing the ductility of MMCs were explored.

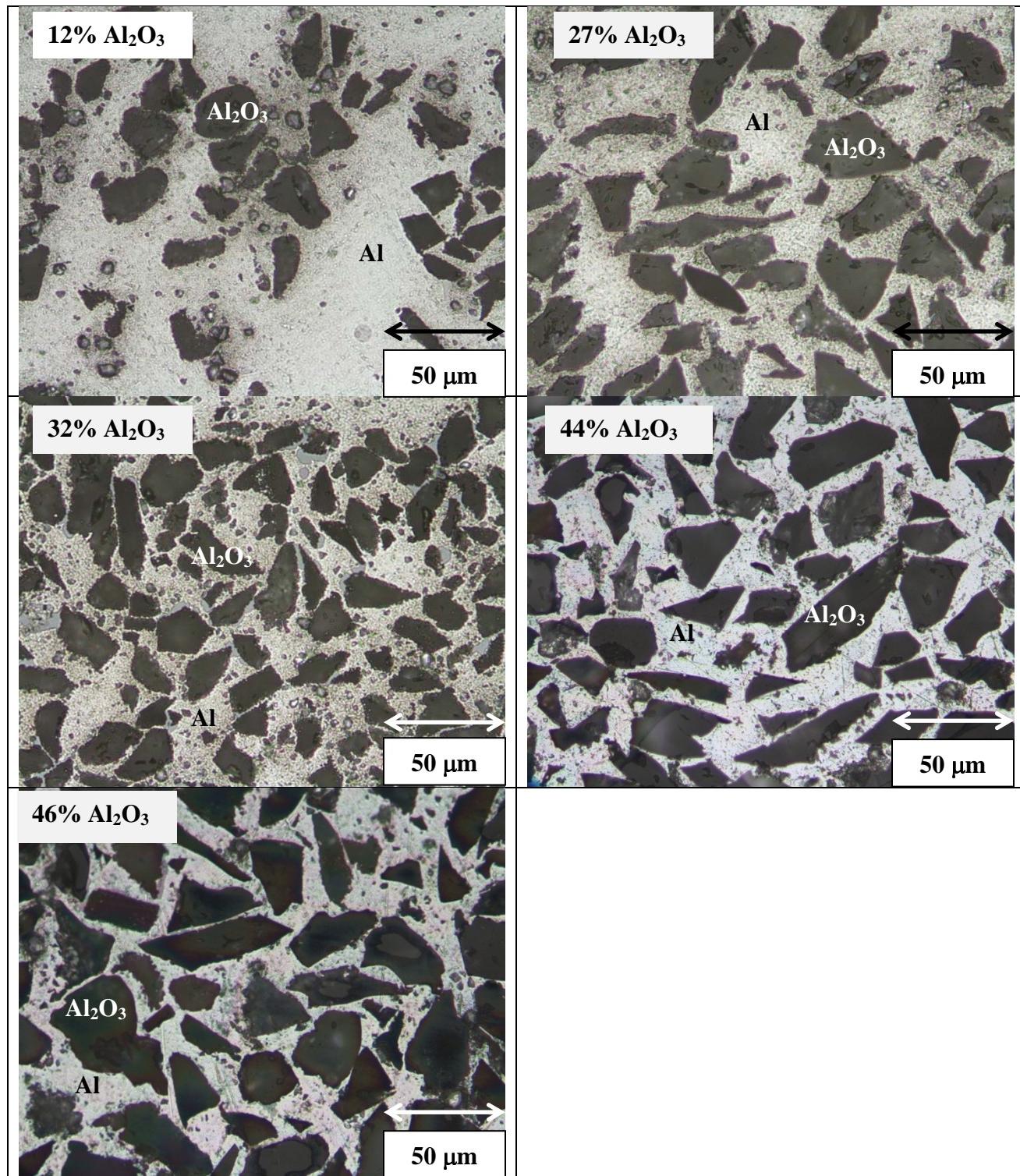
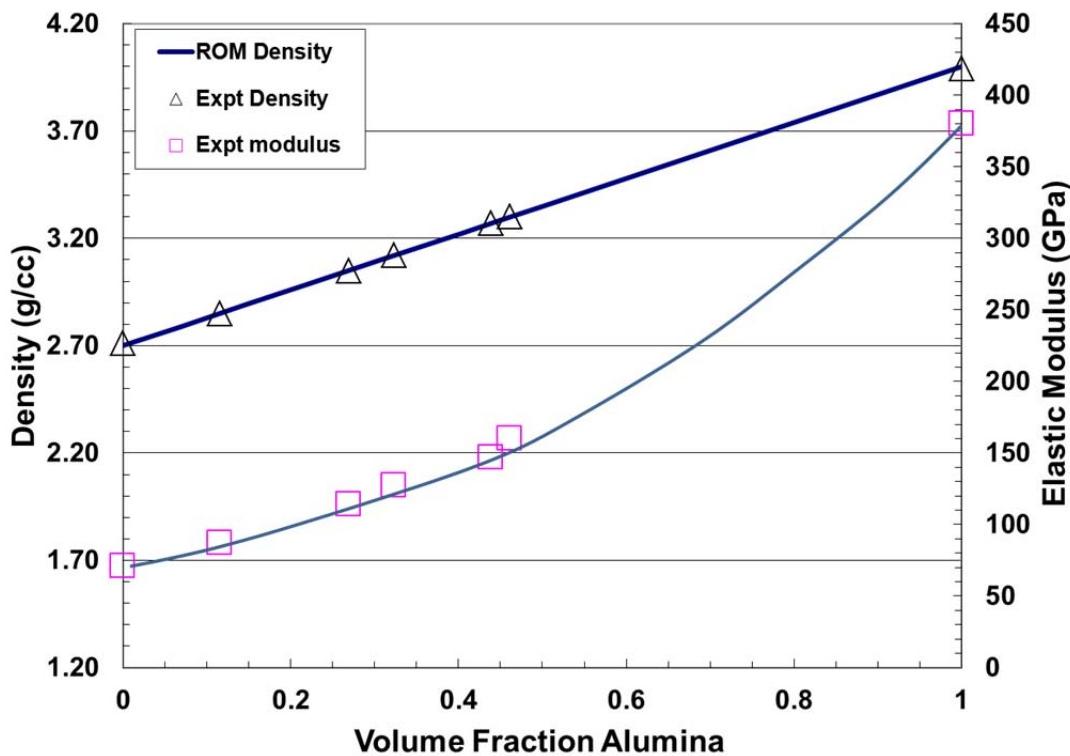


Figure 1. Microstructures of the Al/Al₂O₃ composites with different particulate loadings.

Table 2. Properties of Al/Al₂O₃ MMCs and their comparison with properties of Al/SiC MMCs (as cast)

Material (as cast)	Matrix	ρ (g/cc)	Vp	E (GPa)	UTS (MPa)	e_f (%)	CTE (ppm/K) 20-500°C	CTE (ppm/K) 20-100°C
170 Alloy	N/A	2.71	0	71	99.1 ± 21	30	26.5	22.4
170 + 4 Mg	N/A	2.63	0	69	171.0 ± 25	24	--	--
Al/Al ₂ O ₃	Al 1Mg-0.6Si-0.4-Cu	2.85	0.12	87	111.8 ± 7	1.40	--	--
Al/Al ₂ O ₃	Al-Mg	3.05	0.27	114	103.6 ± 19	0.70	20.4	16.3
Al/Al ₂ O ₃	Al 1Mg-0.6Si-0.4-Cu	3.12	0.32	127	149.6 ± 8	0.96	17.5	14.9
Al/Al ₂ O ₃	Al-4Mg	3.27	0.44	147	168.6 ± 25	0.30	14.1	11.2
Al/Al ₂ O ₃	Al-4Mg	3.30	0.46	160	174.3 ± 9	0.51	14.1	11.2
Al/SiC	Al-10Si	2.78	30	120	206.8 ± 19	0.18	--	15.6
Al/SiC	Al-10Si	2.96	55	202	128.1 ± 28	0.09	--	11.8

ρ – density, Vp – particle volume fraction, E – Elastic Modulus, UTS – ultimate tensile strength, e_f – failure strain, CTE – coefficient of thermal expansion. All properties are in the as-cast (F) condition.

**Figure 2.** Density and Elastic modulus plot for as-cast Al/Al₂O₃ MMCs.

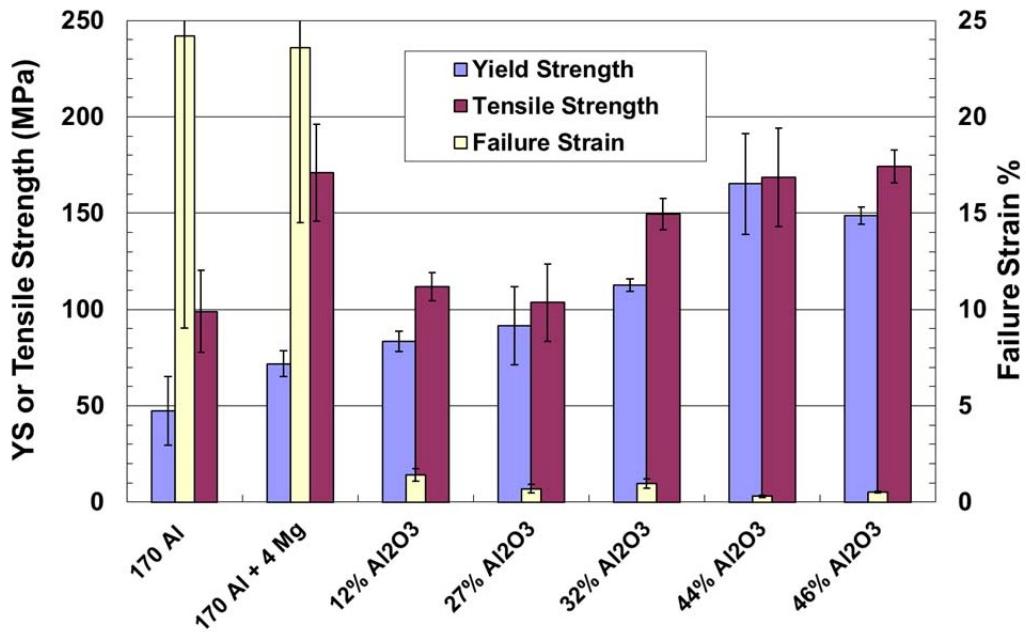


Figure 3. Yield strength, ultimate tensile strength, and failure strain plot for as-cast Al/Al₂O₃ MMCs and base alloys.

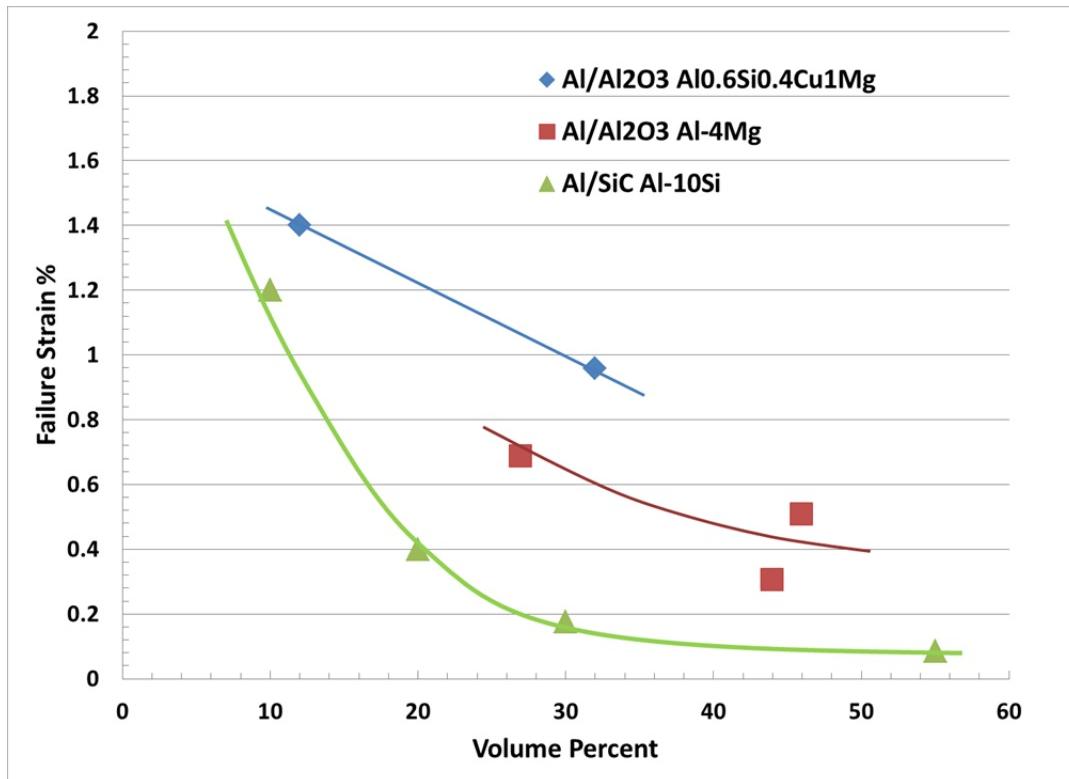


Figure 4. Effect of ceramic content and matrix material on failure strain of as-cast MMCs.

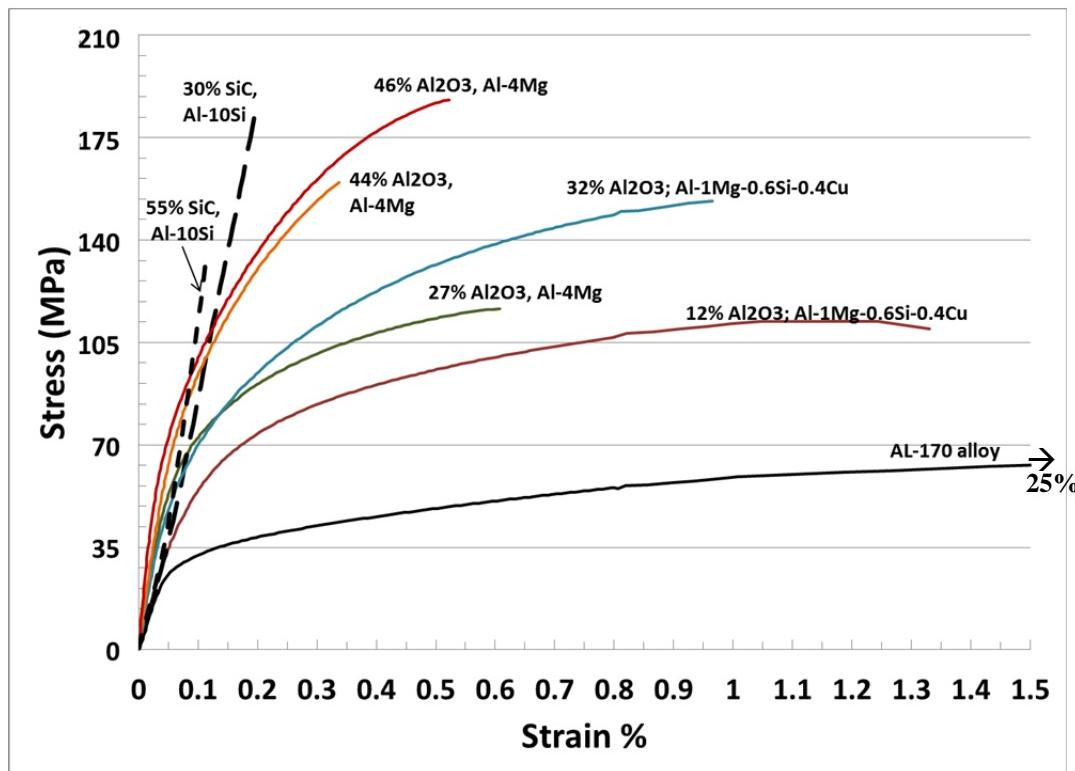


Figure 5. Stress strain curves for as-cast Al/Al₂O₃ and Al/SiC MMCs with various particle contents.

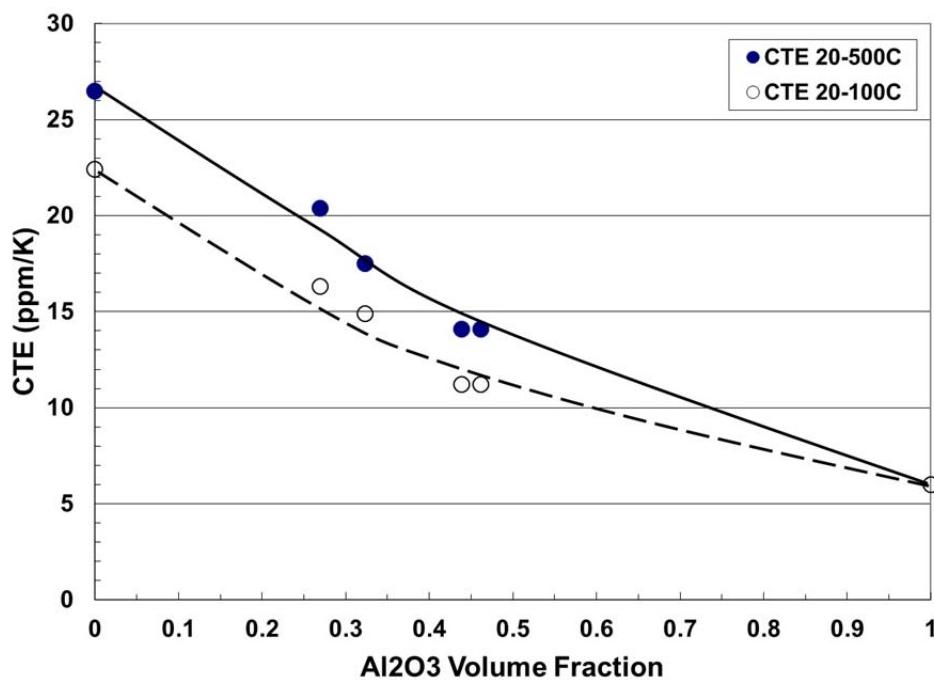


Figure 6. Coefficient of thermal expansion (CTE) plot for as-cast Al/Al₂O₃ composites.

DESIGN OF A MACROCOMPOSITE SYSTEM

Although the Al/Al₂O₃ MMC had higher failure strain than Al/SiC MMC, Al/Al₂O₃ MMC plates broke up into multiple pieces after the first projectile impact and then were unable to stop the subsequent impacts. Thus the failure strain of Al/Al₂O₃ was found to be lower than that desired for obtaining multi-hit capability. Therefore, other means of increasing the ductility of MMCs were explored. Work of Liu et al.^{6,7} indicates that when 300 MPa superimposed hydrostatic pressure was applied to Al/Al₂O₃ MMC (15% particles) the failure strain (a measure of ductility) was quadrupled.

Based on this result, a macrocomposite concept was developed. Here, a third component is added to the Al-MMC/ceramic tile system with higher CTE than that of the MMC and high tensile strength, to put the MMC (and ceramic tiles) under a residual compressive stress after fabrication. An exhaustive search was conducted to identify appropriate reinforcement materials. Since the MMC processing is done with the ductile reinforcement in place, the reinforcement must withstand the MMC processing temperature (~750°C). In addition, resistance to molten Al is desired. Several material were identified with higher CTEs and the requisite temperature capability and reaction resistance (e.g. austenitic stainless steels, Carpenter 21Cr-6Ni-9Mn alloy). Thus the macrocomposite system will include three materials with successively higher CTEs: a ceramic, an encapsulating MMC, and a constraining higher CTE reinforcement. The reinforcement can be in the form of a wire, sheet, expanded sheet, corrugated sheet, 3D periodic structure etc. to provide complete constraint and residual compression.

NUMERICAL MODELING OF AN EXAMPLE MACROCOMPOTE SYSTEM

Numerical modeling was undertaken on an example system to calculate the residual stresses. Also, the relative amounts of the MMC and steel were varied to assess the ability to vary the residual stress. The system that was analyzed consisted of two concentric cylinders: MMC on the inside and steel on the outside. For this analysis, perfect bonding was assumed between the steel and the MMC. The MMC diameter was assumed to be 6.35 mm and the steel thickness was varied from 1.27 mm to 5.08 mm. The MMC was assumed to be Al/SiC with 55% particulates (Density = 2.96 g/cc, E = 202 GPa, CTE = 11.8 ppm/K). Steel with the following properties was used as the constraint layer: Density = 7.8 g/cc, E = 210 GPa, CTE = 19.1 ppm/K). The temperature difference from the processing temperature to room temperature was assumed to be 400°C. Figure 7 shows the results of this analysis.

The analysis predicted that compressive stresses in the range of ~100 to 260 MPa can be generated in the MMC due to the steel reinforcement. Similar stresses are expected to be generated in the Al/Al₂O₃-steel macrocomposite system. Based on the work of Liu at al. described earlier, this stress range is sufficient to increase the ductility of the MMC. Therefore, design and fabrication of a macrocomposite test specimen to verify these predictions was undertaken.

DESIGN AND FABRICATION OF MACROCOMPOSITE SPECIMENS

To experimentally assess the effect of residual compressive stress on the ductility of the MMC, an MMC-steel tensile macro composite specimen was designed. A schematic of this specimen is shown in Figure 8. The specimen consists of a standard tensile test bar for metallic materials per ASTM B 577M-07. The outer shell of the specimen consists of a reinforcing steel alloy tube which is filled with the MMC. The residual stress is systematically varied by selecting the following parameters:

- MMC Type (different MMCs have different CTEs - see Table 2)
- Constraining alloy type: AISI 1018 mild steel (low CTE – 13.4 ppm/K) and 304 stainless steel (high CTE – 16.6 ppm/K) – see Table 1
- Three different ratios of MMC diameter (d_{mmc}) to confining metal diameter (d_c)

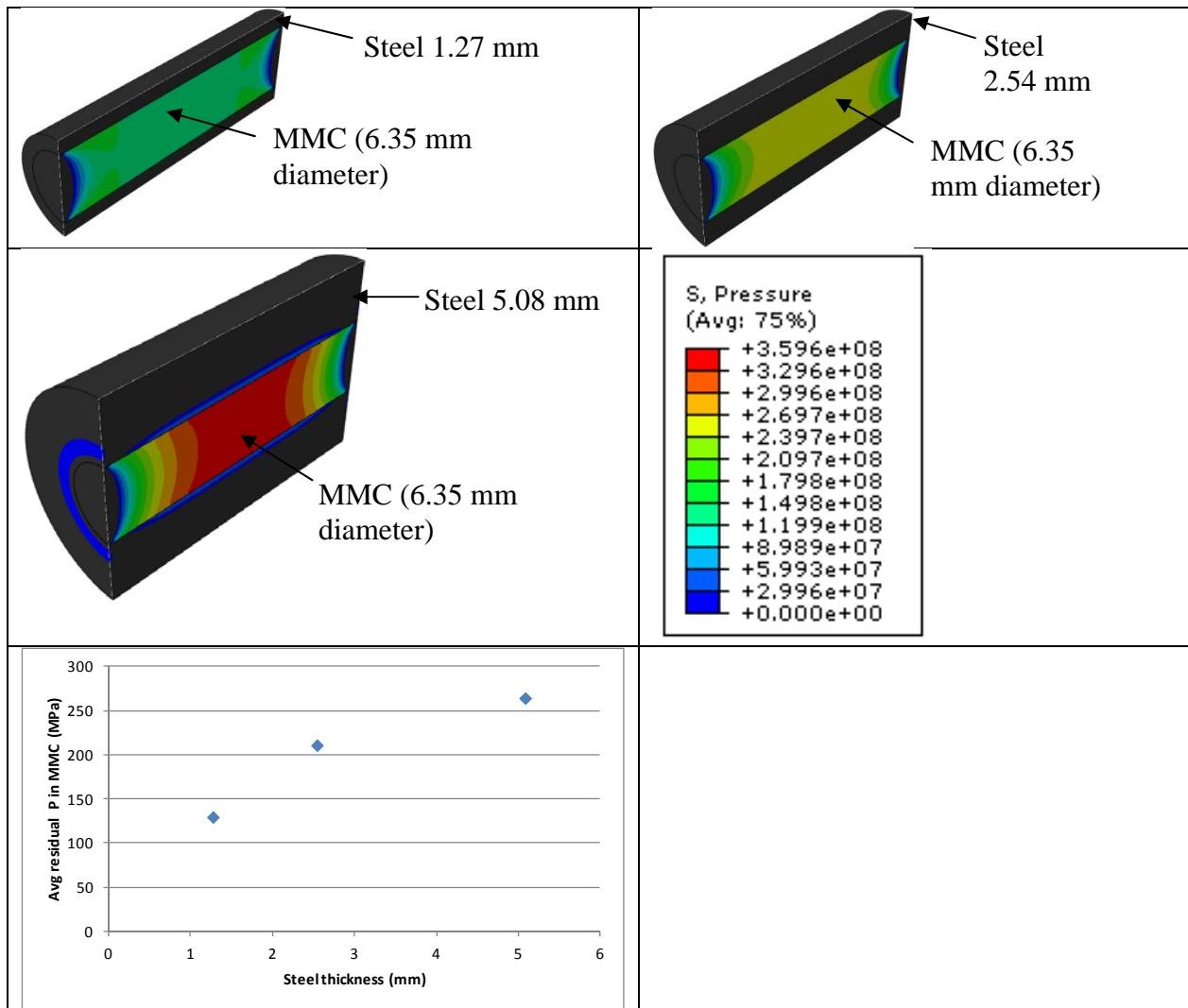


Figure 7. Prediction of residual stresses in the MMC due to steel confinement/reinforcement.

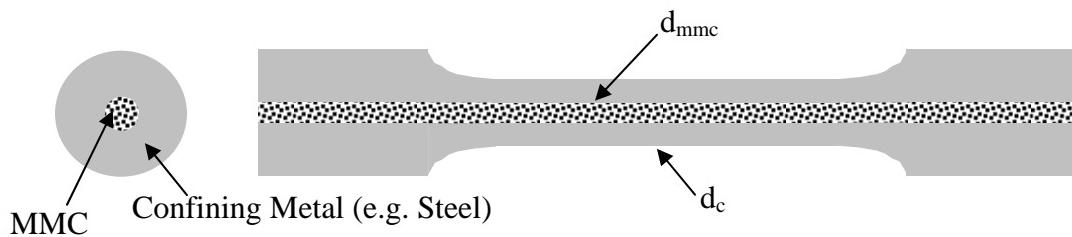


Figure 8. Design of a tensile test sample to evaluate mechanical behavior of MMCs under compressive stress generated by confinement (based on ASTM B557M-07).

A manufacturing process was developed to fabricate the macrocomposite tensile specimens. This process was applied successfully to fabricate the macrocomposite specimens as shown in Figure 9. Future work will include mechanical testing of these specimens, numerical modeling, and analysis of the

results. These data will be used to assess whether we can achieve synergistic effect by combining dissimilar materials at this length scale.

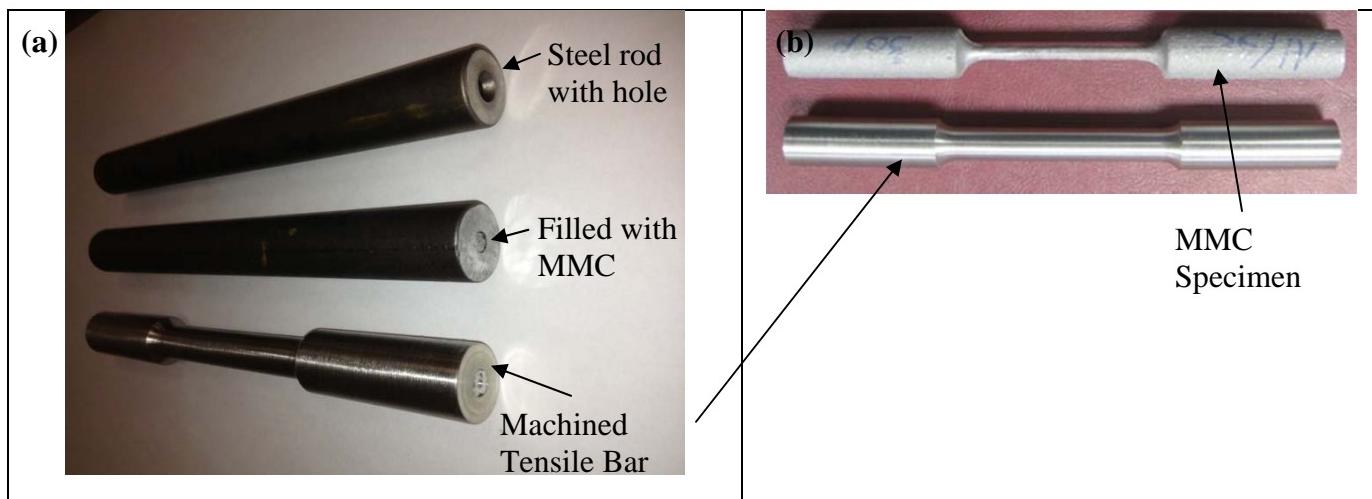


Figure 9. (a) Steel rod with hole for casting macro-composite tensile bars, (b) Steel rods with MMC cast in the center, (c) Macro-composite tensile specimen after machining (left) and as-cast MMC dog bone specimen (right).

The bonding between the cast MMC and the constraining steel layer is also critical for generating the residual compressive stress in the MMC. To evaluate the bonding between the steel and the MMC and the effects of the parameters listed in the previous section, a push-out-type shear specimen was designed as shown in Figure 10a. Again, a fabrication process was developed to make the shear specimens. Using this process, several specimens with different MMC types, steel types, and steel/MMC ratios were successfully fabricated (Figure 10b). Future work will include mechanical testing of these specimens, numerical modeling, and analysis of the results.

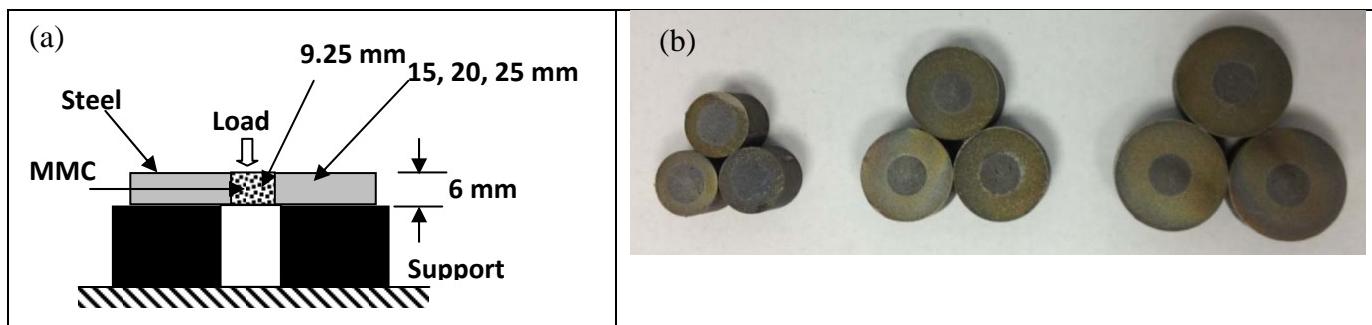


Figure 10. (a) A schematic of the cross-section of a concentric cylinder specimen for measuring steel-MMC bond strength (b) Photo of the specimens fabricated.

SUMMARY AND CONCLUSIONS

Al/Al₂O₃ MMCs with varying alumina content were produced successfully. Characterization of Al/Al₂O₃ MMCs with varying alumina contents showed that density, elastic modulus, and strength

increased with increased particle content. Failure strains (ductility), on the other hand, decreased with increasing particle content. Al/Al₂O₃ MMCs with Al-1Mg-0.6Si0.4Cu matrix showed the highest failure strain, followed by Al/Al₂O₃ MMCs with Al-4Mg matrix, and the Al/SiC MMCs with Al-10Si alloy matrix showed the lowest failure strain. Thus, failure strain was dependent on the matrix purity and extent and type of alloying. The failure strain of Al/Al₂O₃ MMC was lower than that desired for a multi-hit capability, especially as an encapsulant for ceramic tiles.

A literature review of MMCs revealed that under compressive confining pressure, the failure strain (ductility) of MMCs is quadrupled. A macrocomposite system containing high-strength, high ductility, and higher-CTE reinforcement was designed to take advantage of this phenomenon. Numerical modeling of an example system showed that significant confining compressive stress (260 MPa) can be generated in the MMCs due to a higher-CTE ductile reinforcement.

Unit-cell-type macrocomposite tensile and shear specimens were designed to generate the mechanical property data needed to design a macrocomposite system. Fabrication processes were developed and the ability to manufacture the macrocomposite specimens was demonstrated.

Future work will include mechanical testing of these macro-composite specimens, analysis of the data, and numerical modeling. The results obtained will be useful in assessing whether we can achieve synergistic effect by combining dissimilar materials at this length scale.

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